An Estimate of the Geothermal Energy Resource in the Major Sedimentary Basins in the United States

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Keywords

Sedimentary basins, temperature gradient, resource estimate, recovery factor, geothermal energy

ABSTRACT

Recently, there has been renewed interest in recovering the geothermal energy stored in sedimentary basins for electricity production. Because most sedimentary basins have been explored for oil and gas, well logs, temperatures at depth, and reservoir properties such as depth to basement and formation thickness are well known. The availability of this data reduces exploration risk and allows development of geologic exploration models for each basin. This study estimates the magnitude of recoverable geothermal energy from 15 major known U.S. sedimentary basins and ranks these basins relative to their potential. The total available thermal resource for each basin was estimated using the volumetric heat-in-place method originally proposed by (Muffler, 1979). A qualitative recovery factor was determined for each basin based on data on flow volume, hydrothermal recharge, and vertical and horizontal permeability.

Total sedimentary thickness maps, stratigraphic columns, cross sections, and temperature gradient information was gathered for each basin from published articles, USGS reports, and state geological survey reports. When published data were insufficient, thermal gradients and reservoir properties were derived from oil and gas well logs obtained on oil and gas commission databases. Basin stratigraphy, structural history, and groundwater circulation patterns were studied in order to develop a model that estimates resource size, temperature distribution, and a probable quantitative recovery factor.

1. Introduction

Sedimentary basins are present throughout the United States at various depths. Some of the major advantages of producing geothermal fluid from sedimentary basins are that they are porous, permeable, and well characterized from oil and gas drilling. Also, they have known and or proven temperature gradients from oil and gas drilling in the region which lowers exploration risk. Finally, drilling and reservoir fracturing techniques have been widely used and proven effective in sedimentary basins. However, there are some disadvantages of sedimentary basins that also must be addressed. First, the temperatures in the sedimentary basins are usually not anomalously high and to reach rocks with high temperatures, the wells must be drilled to great depths. Second, the use of fluid from sedimentary basins for geothermal production is an emerging industry and has not been widely developed.

The main goal of this study was to provide a "first look" estimate of the total energy present in sedimentary basins. First, relevant data on each basin, such as depth to basement, thickness, rock type, and temperature, was collected and a preliminary review of the basins was completed. The surface extent of the major sedimentary basins in the United States are shown in Figure 1 (Davis, 1984). The major basins were initially screened based on characteristics such as temperature, volume, depth, and reservoir properties including rock type and permeability. First, sedimentary basins considered in this analysis were limited to those with temperatures greater than 100°C, which was assumed

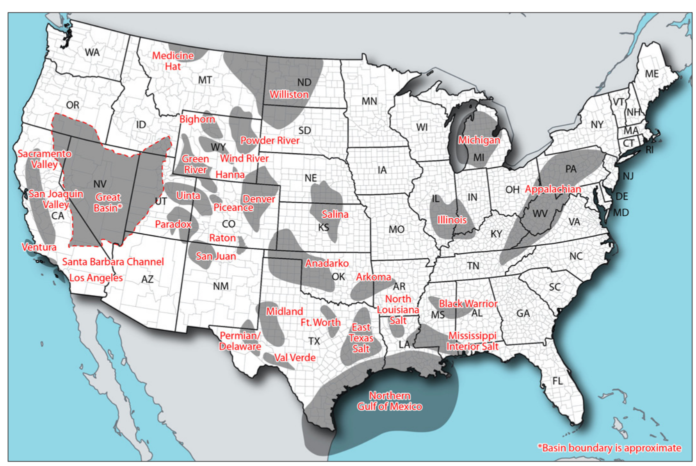

Figure 1. Surface extent of sedimentary basins in the United States (adapted from Davis, 1984; Faulds et al., 2004).

to be the lower bound for geothermal electricity production with the current technology. Second, some basins were excluded due to very low permeability and porosity. From this initial screen, 15 sedimentary basins, listed in Table 1, were chosen for further analysis. All of the basins considered are in the Western portion of the United States and are the location of either present or historical oil and gas exploration. However, the availability of data from the oil and gas exploration varies greatly among the basins analyzed.

Table 1. Sedimentary Basins Included in Analysis.

1	Anadarko	9	Powder River
2	Bighorn	10	Raton
3	Denver	11	Sacramento
4	Ft. Worth	12	San Joaquin
5	Great Basin	13	Uinta
6	Green River	14	Williston
7	Hanna	15	Wind River
8	Permian/Delaware		

The next step was to delineate and map the areal extent of each of the basins considered and develop depth contours for each basin to determine the extent of the basin at each depth. Many of the basins had published depth to basement maps available that showed sedimentary thickness. However, when that was not available, sedimentary thickness contours were derived from shallower horizon maps. With the depth contour maps completed, the amount of rock volume at fluid temperatures above 100°C was determined. A single reliable thermal profile was created for each basin. The thermal profile ignored any regions with temperature anomalies from hydrothermal upwelling of water. The single thermal profile was then used to calculate basin volume as a function of temperature. Next, the volume of rock at each temperature was converted to heat in place using the method developed by Muffler (1979). Finally, a qualitative thermal recovery factor was estimated for each basin by analyzing the critical factors that influence reservoir productivity. A maximum depth cutoff was not considered for this analysis.

2. Data Collection and Spatial Analysis

The data collected for each basin was pulled from eight main data categories listed in Table 2.

Table 2. Data Categories.

	Data Category	Main Data Sources
1	Basin lithology – stratigraphic column	Published literature, oil and gas logs
2	Structural cross-sections	USGS, AAPG
3	Depth to basement maps	AAPG, USGS, and journal articles
4	Temperature logs, thermal profiles, and BHTs from the basin's deepest wells	State geological survey database, Oil & Gas Commission records
5	Production rates and reservoir properties	Published literature, oil and gas logs
6	Hydrologic potentiometric maps	USGS – Water Resources Division reports
7	Hottest documented down hole temperature in each basin	State geological surveys, AAPG
8	Previous geothermal resource assessments	State geological surveys, DOE Technical Reports

All bottom hole temperatures gathered for the basins were corrected using the Kehle correction which for most depths, is considered very similar to the Harrison correction (Kehle et al., 1970). A more detailed temperature correction could not be applied due to limited data on the duration of time after drilling mud circulation ended before the temperature measurement was taken.

For each of the 15 basins, a map was developed showing the regions with temperatures greater than 100°C. Figure 2 is an example of such a map for the Anadarko Basin located in parts of Oklahoma, Texas, and Kansas. Data on the northern edge of the basin was not available so the border in red is the 1500 m thickness contour. The basin extent that was provided is shown in the solid black line that corresponds to the Wichita Mountains Front. On the right, a dashed line represents the edge of the thickness data. The Anadarko Basin is an asymmetric basin in which there are numerous deep oil and gas wells. In this map, sedimentary rocks directly above basement are estimated to have temperatures over 200°C, shown in the light yellow. The blue region shows the extent of the region that has estimated temperatures ranging from 100-150°C. The green region correspondingly has estimated temperatures ranging from 150-200°C. Areas outside of the regions with estimated temperatures less than 100°C are shown in gray.

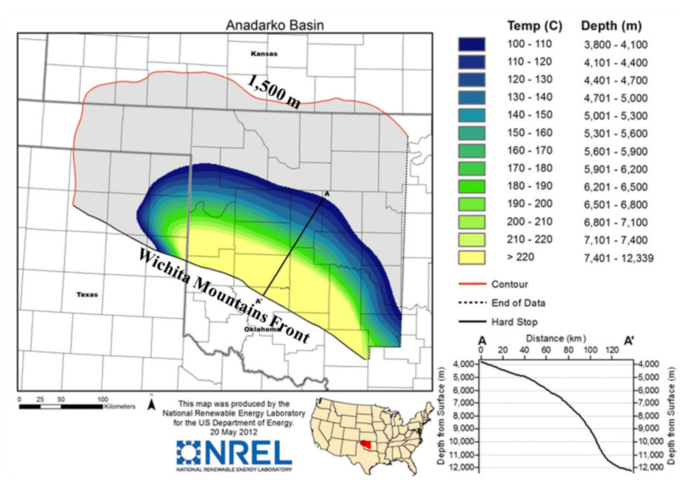

Figure 2. Anadarko basin map showing regions with estimated temperatures greater than 100°C delineated by 10°C temperature increments.

After mapping all of the 15 basins in this manner, some similarities were found. First, most of the basins are axisymmetric and elongated in shape in a certain direction. Second, for most of the basins, data from deep oil and gas wells was available which greatly aided in developing a thermal profile that would be applicable at deeper depths. Finally, in multiple cases, anomalous temperature gradients, such as hydrothermal upwellings, were excluded when establishing the temperature gradient for the basin. The Bighorn Basin in parts of Wyoming and Montana is an example of a basin where anomalous temperature gradients were excluded. This is clear from the temperature extent map for the Bighorn Basin shown in Figure 3. The Bighorn Basin is another axisymmetric basin with temperatures reaching as high as 180°C with the extent of these temperatures shown in the light yellow region. The boundary of the basin was provided and is clear by the solid black line in Figure 3. Moving from the center of the formation to the south, the depth of the formation first decreases so that no regions exist that have temperatures above 100°C and then the depth increases again so that regions with temperatures up to 140°C exist. In the multiple sections of the Bighorn basin, there are well evidenced regions with hydrothermal upwelling that have anomalously high temperatures. Compared to the Anadarko Basin with only some boundary data, data on the extent of the Bighorn basin was provided for all boundaries.

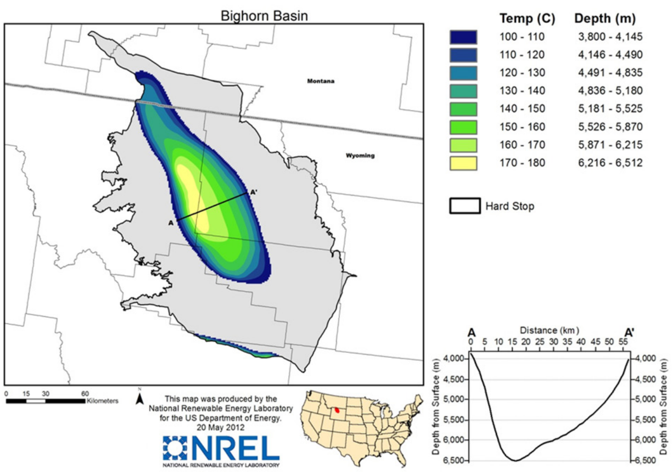

Figure 3. Bighorn basin map showing regions with temperatures greater than 100°C delineated by 10°C temperature increments.

The difference in basin profiles causes the distribution of rock volume for each temperature interval to vary significantly among the basins. An example is shown by comparing the results for the Williston Basin (Figure 4), Uinta Basin (Figure 5), and Anadarko Basin (Figure 6). For the Williston Basin, the rock volume decreases rapidly with depth, indicating a large, saucer-shaped basin. Because of this, the Williston Basin has a large volume of fluid (60,000 km^3) at the lowest temperature interval, but the volume of rock decreases significantly as the temperature interval increases, reaching only 226 km^3 between 150-160 °C. Rock volumes decrease regularly with temperature (depth) in the Uinta basin, indicative of a basin with a V-shape. Analysis of the Anadarko basin shows that rock volumes decrease slowly as temperature increases, suggesting the basin is more cylindrical in profile. Because of this, the volume of rock at high temperatures greater than 220°C in this basin is relatively large.

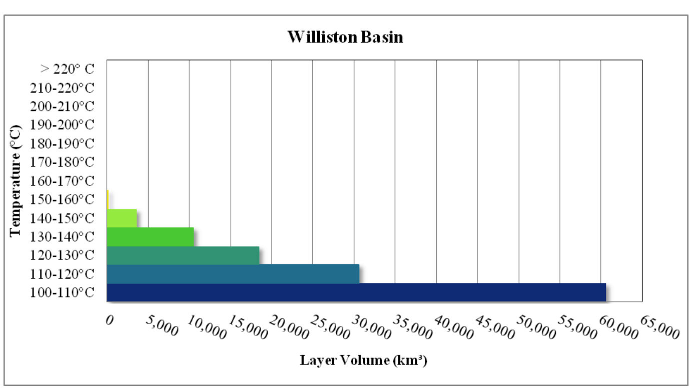

Figure 4. Williston Basin rock volume for each temperature interval.

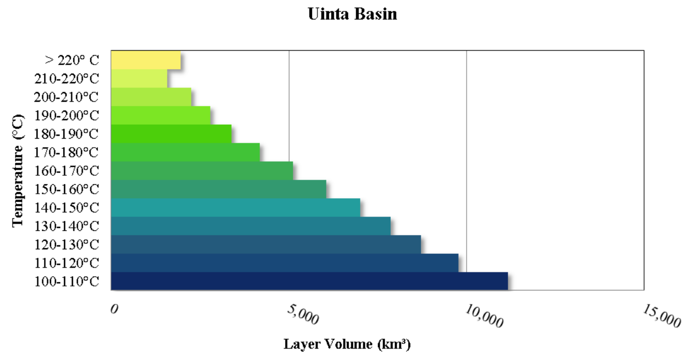

Figure 5. Uinta Basin rock volume for each temperature interval.

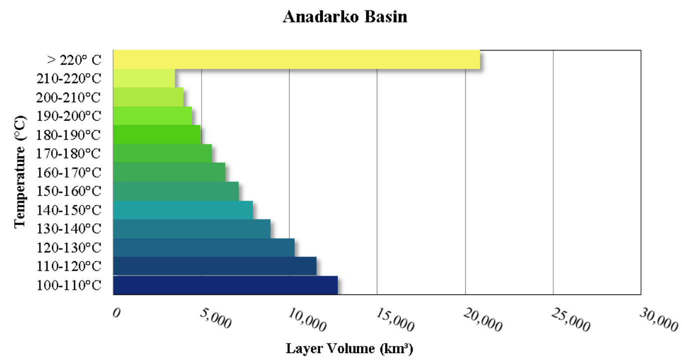

Figure 6. Anadarko basin rock volume for each temperature interval.

The variation in the volume of rock and its temperature among the basins due to their profiles has a significant impact on the sedimentary resource potential. Figure 7 shows a bubble plot that compares the depth, temperature, and volume relationship for nine basins. The slope of the line is the slope of the temperature gradient for each basin. The size of the circle at each point represents the volume of rock present for each depth and temperature value. The large volume of rock between 100-110°C for the Williston Basin is present at a depth of approximately 3,000 m. As the temperature increases, the depth of each volume decreases

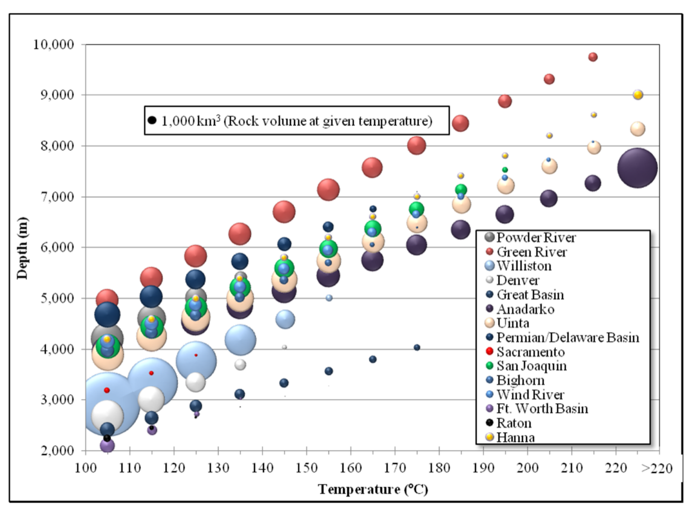

Figure 7. The volume, temperature, and depth relationship for the 15 basins analyzed.

until it terminates for the Williston Basin at about 5,000 m. Most of the basins follow a similar trend, with the volume of rock at each temperature interval decreasing as the depth increases. In comparison, for the Anadarko Basin, the large volume of rock at temperatures greater than 220°C is at a depth of approximately 7,500 m and greater, requiring a much deeper well to recover the heat than for the Williston Basin. From Figure 7 it is also clear that the slope of the temperature gradient for most of these nine basins is very similar. The steepest increase in temperature with depth is found in the Great Basin and the shallowest is found in the Williston Basin.

3. Results

3.1 Total Heat in Place

The total heat in place for each sedimentary basin was calculated based on the volume of rock estimated for each 10°C temperature interval from the basin maps described above. The total heat in place calculation described by Muffler (1979) was used, assuming a reference temperature of 15°C and included the thermal energy in both the rock and the fluid (assumed to be water) in the basin. To calculate the heat in place, some general assumptions need to be made. The assumptions include those for density and heat capacity for both the hot water and rock. The values used for these parameters are listed in Table 3. Also, the porosity is assumed constant at 20% for all basins. The heat in place calculated includes both the heat in the rock and the heat in the water. Recovery of the thermal heat in the rock would require flow through systems with injection and extraction of fluid.

Table 3. Rock and Fluid Property Assumptions.

Property	Value
Rock Density	2.55×10^{12} kg/km^3
Rock Heat Capacity	1 kJ/kg°C
Water Density	1.00×10^{12} kg/km^3
Water Heat Capacity	4.18 kJ/kg°C

The total heat in place for all 15 basins, in order from the largest to smallest, is shown in Figure 8. The bars are color coded to show the quantity of the heat with temperatures from 100-150°C in blue, 150-200°C in green, and 200-250°C in yellow. In all cases except for the Anadarko Basin, the amount of heat in the 200-250°C range is the lowest of all three temperature ranges. This graph demonstrates that the majority of the thermal energy in sedimentary basins is at relatively low temperatures between 100-150°C. It also shows how the total heat in place calculation can be misleading and why the variation in rock volume as a function of temperature discussed above is important. The Williston basin has the largest estimated heat in place due to its large volume, but almost all of this resource is estimated to be at temperature below 150°C. The Anadarko basin ranks second in terms of heat in place, but much of this resource is estimated to be at elevated temperatures, making it a higher quality resource. In the end, both quantity and quality of resource must be considered when evaluating the sedimentary geothermal resource.

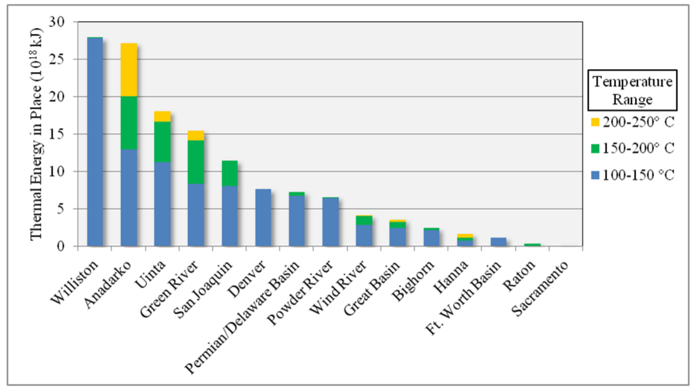

Figure 8. Total heat in place for all 15 basins from highest to lowest.

3.2 Thermal Recovery

Moving from the total heat in place to the recoverable resource available for electricity generation requires an estimate of the recovery factor. Multiple estimates exist in the literature on thermal recovery factors from fractured hydrothermal systems based on empirical data. These recovery factors vary significantly between sources ranging from a low of 5% up to 20% (Williams, 2007). Since there are not sufficient data to develop recovery factors for sedimentary geothermal resources based on empirical data, a qualitative recovery factor was developed based on a general understanding of the main resource characteristics that could influence the recovery efficiency. These include vertical and horizontal permeability, recharge rates, porosity, and connectivity between sand units and their thickness. By gathering data on these factors for the 15 basins, a qualitative estimate of the recovery factor was developed for each basin. Four main factors were chosen for the estimate—flow volume, hydrothermal recharge, vertical permeability (k_z), and horizontal permeability (k_x/k_y)—as the most critical on the reservoir productivity. The qualitative reservoir productivity definitions were compiled in a matrix from high to low recovery efficiency with four main characteristics along the top (Table 4).

Table 4. Qualitative Reservoir Productivity Matrix.

Flow Volume	Hydrothermal Recharge	Vertical Permeability	Horizontal Permeability
Good Reservoir Productivity			
High flow volumes proven	Strong hydrothermal recharge	High vertical permeability	>10md permeability over 200m interval
High flow volumes indicated	Strong hydrothermal recharge	Some vertical permeability	> 5md permeability over 100m interval
Moderate flow volumes	Fractures, some compartmentalization	Low vertical permeability	>20% net/gross interval carbonate and sandstones
Moderate to low flow volume	Reservoir compartmentalized	Low vertical permeability	>5% net/gross interval carbonate and sandstones
Low flow volume	Reservoir compartmentalized with sealing faults	No vertical permeability	Shale throughout producing interval with low permeability
Poor Reservoir Productivity			

Figure 9 depicts how each basin fits into the qualitative recovery factor matrix. The expected thermal recovery factors vary within each basin based on variations in lithologic and diagenetic effects. All basins display a range of values, as reservoir quality, facies, and lithology within the thermal window vary at depth. This plot can be helpful to compare basin recoverability factors. For example, the Bighorn basin stands out with optimal properties with high reservoir flow volumes, strong hydrothermal recharge, and demonstrated vertical and horizontal permeability. In contrast, the Green River basin has compartmentalized, shale rich reservoirs, and falls within the lowest expected thermal recovery factor range. The data sources used for each basin to develop the temperature profile maps (basin thickness, basin depth, basin boundary, and temperature with depth) and to determine a qualitative recovery factor are listed in Table 5.

4. Conclusions

Several conclusions can be drawn on the potential of geothermal electricity production from sedimentary basins in the U.S. based on this first-order analysis. First, the overall resource potential of the 15 basins studied is quite large at 1.35 $x10^{20}$ kJ. However, the majority of the thermal energy is at relatively low temperatures between 100-150°C. Second, there is significant

Table 5. Sources by Basin.

	Basin	General Sources	Recovery Factor Sources			
			Flow Volume	Recharge	k_z	k_x/k_y
1	Anadarko	(Carter et al., 1998; Hester, 1997; Price, 1981)	(Nelson, 2009; Steinmetz, 1978)	(Henry and Hester, 2006)	(Henry and Hester, 2006)	(Henry and Hester, 2006; Hester, 1997)
2	Bighorn	(Finn, 2010a, b; Finn et al.; GIS Spatial Data Team, 2010; Hinckley, 1983; Quillinan, 2010)	(Garfield et al., 1992; Morgan et al., 1978)	(Bredehoeft and Bennett, 1972)	(Hinckley et al., 1982; Montgomery, 1996; Morgan et al., 1978; Wo and Yin, 2011)	(Montgomery, 1996; Morgan et al., 1978; Pranter et al., 2005)
3	Permian/ Delaware	(Erdlac Jr, 2006; Hills, 1984)	(Dutton et al., 2005; Erdlac Jr, 2006; Lee and Williams, 2000; Steinmetz, 1978; Tennyson et al., 2012)	(Lee and Williams, 2000; Mace et al., 2005; Tinker, 1996)	(Dutton, 2008; Erdlac Jr, 2006; Lee and Williams, 2000; Tinker, 1996)	(Dutton, 2008; Erdlac Jr, 2006; Tinker, 1996; Walker and Harris, 1986)
4	Denver	(Belitz and Bredehoeft, 1988)	(Brainerd et al., 1955; Higley and Cox, 2005)	(Nelson and Santus, 2011; Topper et al., 2003)	(Higley, 1988; Lee and Bethke, 1994; Nelson and Santus, 2011)	(Higley, 1988; Lee and Bethke, 1994; Nelson and Santus, 2011)
5	Ft. Worth	(Negraru et al., 2009; Pollastro et al., 2007; Zhao et al., 2007)	(Steward, 2011)	(Mace et al., 2005)	(McDonnell et al., 2007; Pollastro et al., 2007)	(Mace et al., 2005; Pollastro et al., 2003)
6	Great Basin	(Anna et al., 2007; Jachens et al., 1996)	(Blackett and Wakefield, 2002)	(Goff et al., 1994; Grauch et al., 2000)	(Barker et al., 1995; Peterson and Grow, 1995)	(Allis et al., 2011)
7	Green River	(Clarey et al., 2010; Spencer et al., 1985)	IHS Production Data, 2011	(Clarey et al., 2010)	(Brinkerhoff, 2011; Johnston et al., 2010)	(Billingsley and Henry, 2005; Brinkerhoff, 2011; Cramer, 2005; Spencer, 1989; Spencer et al., 1985)
8	Hanna	(Blackstone Jr, 1993; Hinckley and Heasler, 1984)	(Berdan, 1986; Dyman and Condon, 2007; Hinckley and Heasler, 1984)	(Berdan, 1986; Wilson et al., 2001)	(Wilson et al., 2001)	(Dyman and Condon, 2007; Perman, 1990)
9	Powder River	(Flores et al., 2004)	(IHS Production Data, 2011)(Anna, 2010)	(Buelow et al., 1986; Hodson et al., 1973)	(Anna, 2010; Buelow et al., 1986)	(Anna, 2010; Buelow et al., 1986; Glaze and Keller, 1965)
10	Raton	(Broadhead, 2010; Kehle et al., 1970; Morgan, 2009)	(Higley et al., 2007)	(Keighin, 2005)	(Woodward, 1984)	(Sares et al., 2009; Woodward, 1984)
11	Sacramento	(Cherven, 1983)l	(Cherven, 1983; Gas, 1998)	(Cherven, 1983; Myer, 2005)	(Hobson, 1951; Magoon and Valin, 1995; McPherson and Garven, 1999; Sanyal et al., 1993)	(McPherson and Garven, 1999; Zieglar and Spotts, 1978)
12	San Joaquin	(Cherven, 1983; Perez and Boles, 2004; Wilson et al., 2000; Wilson et al., 1999; Zhang et al., 2005; Zieglar and Spotts, 1978)	(Gas, 1998)	(Boles and Ramseyer, 1987; Hayes and Boles, 1993)	(Scheirer and Magoon, 2007; Taylor and Soule, 1993; Zieglar and Spotts, 1978)	(Scheirer and Magoon, 2007; Taylor and Soule, 1993; Webb, 1981; Zieglar and Spotts, 1978)
13	Uinta	(Lucas and Drexler, 1976; Roberts, 2003; Sanborn, 1977)	(Bredehoeft et al., 1994)	(McGee et al., 1989; Zhang et al., 2009)	(McGee et al., 1989; Mitra and Mount, 1998; Sanborn, 1977)	(Bredehoeft et al., 1994; Spencer, 1987)
14	Williston	(Burrus et al., 1996; Gerhard and Anderson, 1979)	(Garfield & Petroleum Co., 2009; Powley, 2007; Sonnenberg and Pramudito, 2009)	(Bachu and Hitchon, 1996; Gerhard et al., 1982; Gosnold et al., 2011)	(Burrus et al., 1996; Dembicki Jr and Pirkle, 1985)	(Burrus et al., 1996; Dembicki Jr and Pirkle, 1985; Kent and Christopher, 1994; Pollastro et al., 2008)
15	Wind River	(Hinckley and Heasler, 1987)	(Perry and Flores, 1997)	(Richter Jr, 1981; Whitcomb and Lowry, 1968)	(Johnson et al., 2007; Li et al., 2012; Westphal et al., 2004)	(Johnson et al., 2007; Li et al., 2012; Westphal et al., 2004)

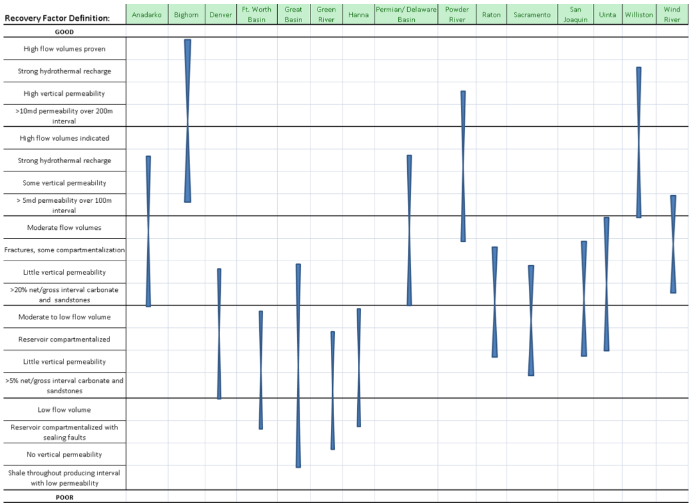

Figure 9. Qualitative plot of basin recovery factors.

variation among the basins in terms of reservoir temperature and depths. For example, the Anadarko Basin has the second largest total heat in place due to the large amount of rock volume at temperatures greater than 220 °C. In comparison, the Williston basin has the largest resource due to its much larger rock volume, but the resource lies almost entirely in the lower temperature range. The temperature gradient of the basins ranges as well, with some reaching a fluid temperature of 100°C at 2,500 m while others reach 100°C at more than 4,500 m. Depth is an important criterion to consider when comparing basins due to the increased cost of drilling deeper wells.

One area where more research is required is on estimating thermal recovery factors. Currently, little quantitative data exist on thermal recovery factors in sedimentary basins. A qualitative estimate of the recovery factors for each basin was developed that incorporated the critical factors on natural reservoir productivity. The recovery factor within each basin can have a sizeable variation as well as among the different basins. To determine quantitative recovery factors for each basin, a more in depth study is required. Including the influence of reservoir stimulation and enhanced recovery methods could also provide an upper bound on the potential recovery factors.

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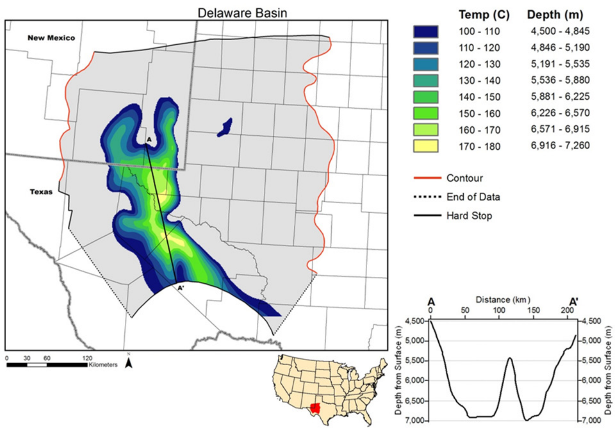
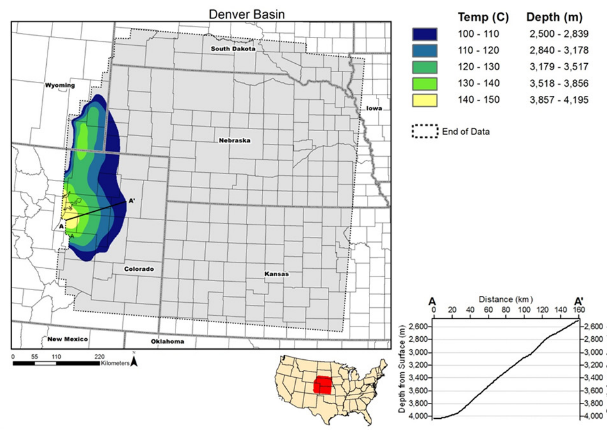
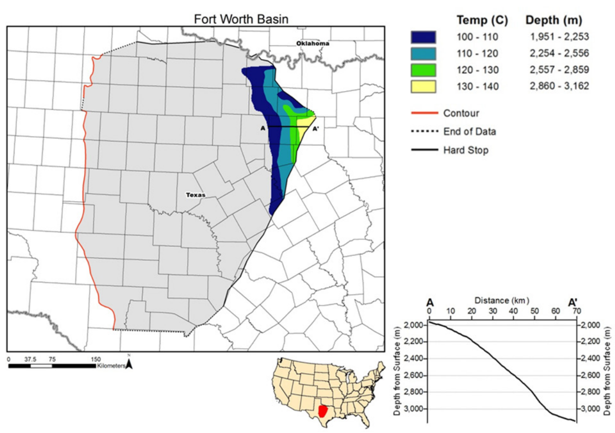
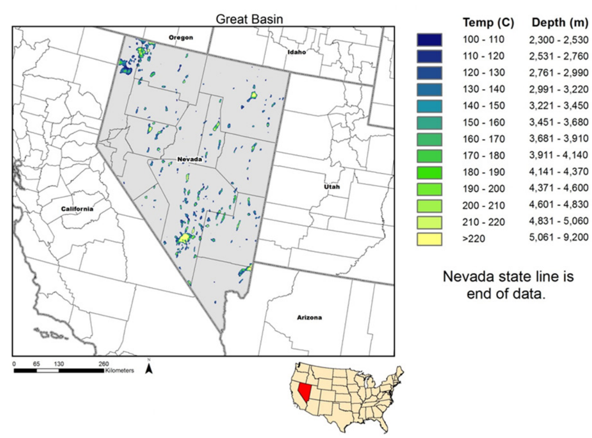
Appendix: Temperature With Depth Maps for Basins 3-15

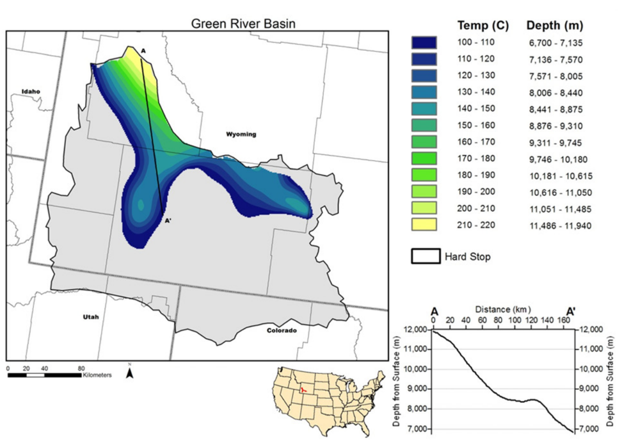
3) Permian/Delaware Basin,
4) Denver Basin,
5) Fort Worth Basin,
6) Great Basin,
7) Green River Basin,
8) Hanna Basin,
9) Powder River Basin,
10) Raton Basin,
11) Sacramento Valley,
12) San Joaquin Valley,
13) Uinta Basin,
14) Williston Basin, and
15) Wind River Basin.

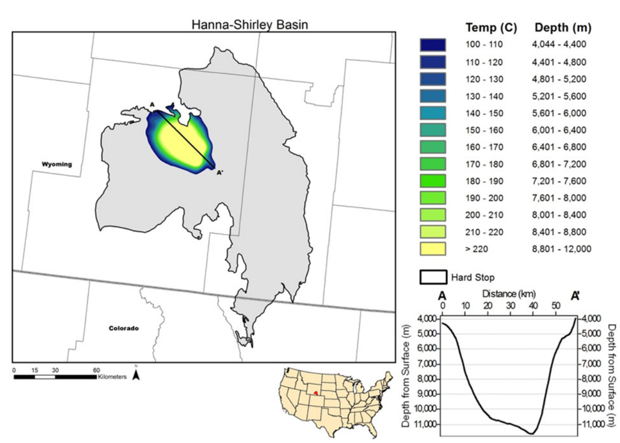


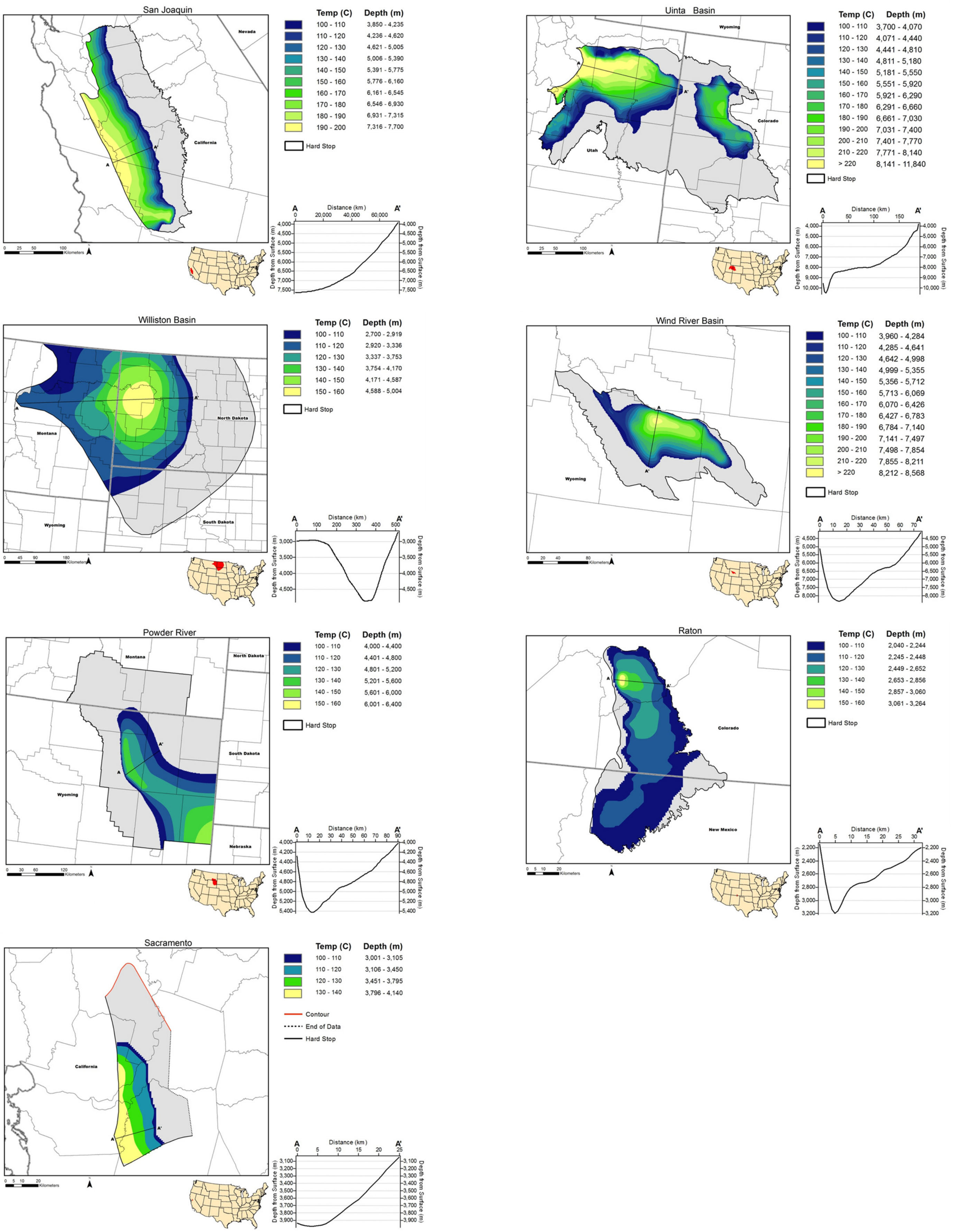












San Joaquin
Nevada
California
Temp (C) Depth (m)
100 - 110 3,850 - 4,235
110 - 120 4,236 - 4,620
120 - 130 4,621 - 5,005
130 - 140 5,006 - 5,390
140 - 150 5,391 - 5,775
150 - 160 5,776 - 6,160
160 - 170 6,161 - 6,545
170 - 180 6,546 - 6,930
180 - 190 6,931 - 7,315
190 - 200 7,316 - 7,700
Hard Stop
Distance (km)
Depth from Surface (m)
Uinta Basin
Wyoming
Utah
Colorado
Temp (C) Depth (m)
100 - 110 3,700 - 4,070
110 - 120 4,071 - 4,440
120 - 130 4,441 - 4,810
130 - 140 4,811 - 5,180
140 - 150 5,181 - 5,550
150 - 160 5,551 - 5,920
160 - 170 5,921 - 6,290
170 - 180 6,291 - 6,660
180 - 190 6,661 - 7,030
190 - 200 7,031 - 7,400
200 - 210 7,401 - 7,770
210 - 220 7,771 - 8,140
> 220 8,141 - 11,840
Hard Stop
Williston Basin
Montana
North Dakota
Wyoming
South Dakota
Temp (C) Depth (m)
100 - 110 2,700 - 2,919
110 - 120 2,920 - 3,336
120 - 130 3,337 - 3,753
130 - 140 3,754 - 4,170
140 - 150 4,171 - 4,587
150 - 160 4,588 - 5,004
Hard Stop
Wind River Basin
Wyoming
Temp (C) Depth (m)
100 - 110 3,960 - 4,284
110 - 120 4,285 - 4,641
120 - 130 4,642 - 4,998
130 - 140 4,999 - 5,355
140 - 150 5,356 - 5,712
150 - 160 5,713 - 6,069
160 - 170 6,070 - 6,426
170 - 180 6,427 - 6,783
180 - 190 6,784 - 7,140
190 - 200 7,141 - 7,497
200 - 210 7,498 - 7,854
210 - 220 7,855 - 8,211
> 220 8,212 - 8,568
Hard Stop
Powder River
Montana
North Dakota
South Dakota
Wyoming
Nebraska
Temp (C) Depth (m)
100 - 110 4,000 - 4,400
110 - 120 4,401 - 4,800
120 - 130 4,801 - 5,200
130 - 140 5,201 - 5,600
140 - 150 5,601 - 6,000
150 - 160 6,001 - 6,400
Hard Stop
Raton
Colorado
New Mexico
Temp (C) Depth (m)
100 - 110 2,040 - 2,244
110 - 120 2,245 - 2,448
120 - 130 2,449 - 2,652
130 - 140 2,653 - 2,856
140 - 150 2,857 - 3,060
150 - 160 3,061 - 3,264
Hard Stop
Sacramento
California
Temp (C) Depth (m)
100 - 110 3,001 - 3,105
110 - 120 3,106 - 3,450
120 - 130 3,451 - 3,795
130 - 140 3,796 - 4,140
Contour
End of Data
Hard Stop
Kilometers